The visual perception of outdoor angular spatial relationships

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A single experiment evaluated younger and older observers' ability to judge angular spatial relationships in an ordinary outdoor environment. Previous research from multiple laboratories has found that the visual ability to perceive distance is either well-maintained or improves with advancing age. The present experiment investigated whether this age-related equivalence or superiority also occurs for other spatial abilities, such as the ability to judge angles. Thirty adults judged 12 angles formed from trees, signs, light poles, and stone benches. The observers' overall performance was good: 74% of the variance in the judged angles could be accounted for by variance in the physical stimulus angles (overall Pearson *r* correlation coefficient was 0.86). The judgments of the older observers were nevertheless more accurate than those made by the younger observers (Cohen's d was 0.72). A detailed analysis of the observers' judgments revealed consistent local distortions of particular stimulus angles such that some angles were perceived to be much larger than they actually were (physically), whereas other stimulus angles were perceived to be much smaller than their physical magnitude. These local distortions in perceived angle magnitude may be related to the presence of environmental features that are associated with (linear) perspective.

Introduction

Aging is known to affect a wide variety of visual abilities. For example, aging is associated with significant impairments for many motion-related tasks, such as the ability to perceive/judge the speed (Norman, Ross, Hawkes, & Long, 2003; Raghuram, Lakshminarayanan & Khanna, 2005; Snowden & Kavanagh, 2006) and direction (Atchley & Andersen, 1998; Ball & Sekuler, 1986; Bennett, Sekuler, & Sekuler, 2007; Billino, Bremmer, & Gegenfurtner, 2008; Pilz, Miller, & Agnew, 2017; Shain & Norman, 2018) of moving objects. Aging also negatively affects the ability to perceive/recognize patterns and objects camouflaged by noise (Norman, Carmichael, Hagan, Ramirez, et al., 2025; Norman, Graham, & Eaton, 2025). The effects of aging upon visual abilities, however, are not always negative. Older adults, for example, are either equivalent to younger adults (Norman, Baig, Eaton, Graham, & Vincent, 2022; Norman, Dukes, Shapiro, & Peterson, 2020; Norman, Holmin, & Bartholomew, 2011) or exhibit superior performance (Bian & Andersen, 2013; Norman, Adkins, Norman, Cox, & Rogers, 2015) for tasks involving the judgment of environmental distance and size. As an example of a study that found an age-related superiority for the perception of environmental distance, consider the experiments conducted by Bian and Andersen (2013). In their experiment 1, for example, Bian and Andersen placed a brick either 4, 6, 8, 10, or 12 m away from the participants in a grassy field. On any given trial, the observers' task was to simply indicate the egocentric distance from themselves to the brick. The judgments of the older adults were quite accurate—the slope of the linear function relating perceived distance to actual distance was 0.95. The younger adults, however, underestimated the stimulus distances and their judgments were quite inaccurate—their average

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slope (relating perceived and actual distance) was 0.56. As an example, the younger adults perceived the 10-m physical stimulus distance to be only 6.2 m in extent, reflecting a severe perceptual compression of distance in depth, a result that has been frequently obtained in past studies (Da Silva, 1985; Gilinsky, 1951; Kuroda, 1971; Loomis, Da Silva, Fujita, & Fukusima, 1992; Norman et al., 2015; Norman et al., 2024; Norman, Todd, Perotti, & Tittle, 1996; Philbeck, 2000; Wagner, 1985). It is important to note, however, that this age-related superiority in distance perception has only been obtained with regard to accuracy. Although Bian and Andersen did not evaluate precision, Norman et al. (2015) did evaluate the precision of their observers' judgments. In the experiment conducted by Norman et al. (2015), although their older observers' judgments of distance were more accurate than those of the younger observers (thus replicating the basic finding of Bian & Andersen), they were not more precise (compare the left and right panels of Norman et al.'s Figure 3).

Two previous studies (Hecht, van Doorn, & Koenderink, 1999; Wagner, 1985) have evaluated observers' ability to perceive angles in actual outdoor environments. In the first experiment, Wagner asked five observers to judge all possible angles that existed between ten stakes randomly positioned within a 40 × 40 m area of a grassy field. In the other study, Hecht, van Doorn, and Koenderink asked observers to judge the magnitude of the convex and concave corners (i.e., vertical dihedral angles) that exist wherever the walls of buildings intersect. Wagner's observers were unable to judge outdoor angles accurately. His observers' perceived outdoor angles were consistent with a severe affine compression of visual space (in the in-depth direction) of 50% to 60%. Hecht et al. also found evidence of compression of visual space, but it was smaller. In Hecht et al.'s experiment 1, 74% of the observers' judgments were within 10° of the actual stimulus angles. In their pilot experiment, however, the stimulus right angle (p. 1275) "was overestimated by 21 degrees from the far vantage point." Hecht et al. concluded (p. 1281) by saying "A flattening effect was found at observer distances of between 5 and 15 m. The angles of vertical building corners were misjudged in a way that is compatible with a subjective compression of visual space."

One can describe spatial relationships between environmental objects entirely in terms of distances and angles (e.g., consider polar coordinate systems). We know from existing literature (Bian & Andersen, 2013; Norman et al., 2011; Norman et al., 2015; Norman et al., 2020; Norman et al., 2022) that older adults can effectively perceive environmental distances. When an age-related difference has been found, the performance of older adults has usually been superior to that exhibited by younger adults (Bian & Andersen, 2013; Norman et al., 2015). This finding of an age-related superiority for the perception of environmental distance (specifically, that older adults' judgments of distance are more accurate) is especially striking, because this result has been obtained by two separate laboratories for quite different experiments (e.g., the distances investigated by Bian & Andersen in experiments 1–3 were outdoors and large, whereas the distances investigated by Norman et al. (2015) were indoors and small). Because one fundamental aspect of spatial relationships (environmental distance) has been repeatedly shown (in four separate experiments) to be perceived more accurately by older adults, we hypothesize that, in the current experiment, if an age-related difference in accuracy is found (with regard to perceived angles), that the older adults' judgments will again be superior to those of younger adults. The primary goal of the current experiment was to test this hypothesis and evaluate for the first time older adults' ability to judge angles in ordinary outdoor environments. In the few studies that have been conducted on human observers' ability to judge outdoor environmental angles, only small numbers of participants were evaluated. Only five observers participated in the pioneering experiment of Wagner (1985), and seven and eight observers participated in Hecht et al.'s (1999) pilot experiment and experiment 1, respectively. A secondary purpose of the current experiment was to evaluate the ability of human adults to perceive and judge environmental angles with a much larger sample of observers (i.e., 30 observers participated in the current experiment versus 5 to 8 observers in previous experiments).

Beyond linear regressions (evaluating the relationship between the physical stimulus angles and the judged angles) for each of the individual observers, we planned three additional analyses before the experiment: one to evaluate the observers' overall accuracy, one to evaluate reliability, and one to evaluate whether the observers' angle judgments were consistent with Euclidean geometry. As mentioned, previous research has repeatedly demonstrated that the distance judgments of older adults are more accurate than those of younger adults (Bian & Andersen, 2013; Norman et al., 2015). Because of these previous results, our current hypothesis with regards to accuracy is directional; we accordingly decided a priori to use a one-tailed *t* test when assessing accuracy. All other statistical tests (e.g., regarding reliability and consistency with Euclidean geometry) were two tailed.

Methods

Apparatus and experimental stimuli

An Apple M2 MacBook Air computer was used to generate the random order of experimental stimuli and to record the observers' angle judgments. There were 12 outdoor stimulus angles in the experiment, formed from

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Figure 1. A photograph of the experimental outdoor scene on the Western Kentucky University campus, taken from the viewpoint of the observers. The location of objects used in the experiment (trees, signs, light poles, and stone benches) are labelled with the letters A through S. This photograph was taken by the first author (J.F.N.) using an Apple iPhone 15 camera.

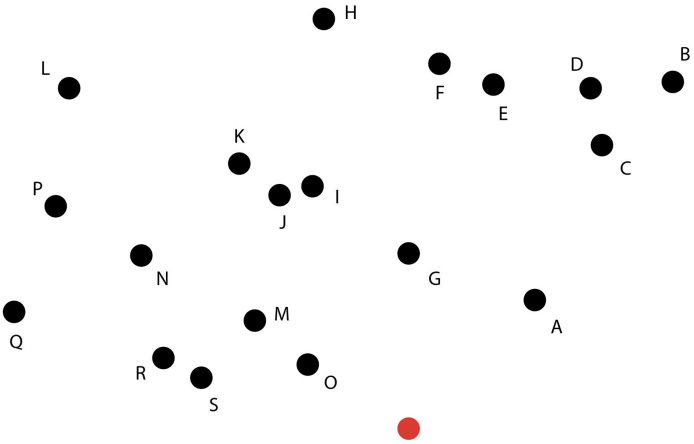

Figure 2. An overhead view of the actual spatial arrangement of objects in the scene; the letters correspond with those used in Figure 1 and indicate the locations of trees, signs, light poles, and stone benches. The red circle indicates the viewpoint/location of the observers.

the 19 locations (A–S) highlighted in Figures 1 and 2. The distances from the observer (location marked with a red circle in Figure 2) to the various object locations forming the angles ranged from 6.45 m (location O) to 25.98 m (location L). The average distance from the observer to the 19 object locations was 16.8 m. The various distances and angles within the scene were measured with a Topcon model GTS-602AF Geodetic Total Station. The GTS-602AF can measure angles to within 2 arcseconds. The Topcon electronic distance measurement system uses a laser diode source in conjunction with a prism reflector placed at the target. The 12 stimulus angles were representative of all angles within the scene and were specifically chosen so that the observers had a wide range of angle magnitudes to judge. The exact stimulus angles are shown in Figure 3 and range in magnitude from HNK (9.16°) to QRM (140.64°). Some stimulus angles were relatively close to the observer (e.g., RMS), whereas others (e.g., HIC) were farther away.

Procedure

Each observer participated in two experimental sessions of 12 trials each. All 12 stimulus angles were judged in each session. The observers participated in two sessions so that the observers' reliability could be assessed in addition to accuracy. The observers viewed the scene binocularly and were allowed to move their head, but had to remain in position (remain at the location indicated by the red circle in Figure 2) while viewing the stimulus angles and making judgments. For each trial, the experimenters would indicate the angle to be judged by placing orange cones immediately adjacent to the objects defining the stimulus angle. For example, if an observer was judging the angle EGF, two small orange cones (18.0 cm tall and 13.5 cm in diameter at the base) would be placed at locations E and F, and a large orange cone (44 cm tall and 27 cm in diameter at the base) would be placed at location G. The large cone indicated to the observer the central vertex of the stimulus angle to be judged (see Figure 4). The entire set of 24 judgments took approximately 45 to 75 minutes for each observer. The observers made their angle judgments by adjusting an angle on the Apple M2 MacBook Air laptop screen until that adjustable angle matched the magnitude of the stimulus angle viewed on each trial—the adjustable angle's magnitude could be adjusted upward or downward in

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Stimulus Angles (in degrees)

HNK: 9.16
EGF: 17.39
RMS: 24.82
CAE: 34.35
HGE: 46.53
PKR: 55.48
BAH: 69.25
HIC: 78.08
SML: 98.47
OID: 110.89
KJI: 126.44
QRM: 140.64

Figure 3. The physical magnitudes of the 12 stimulus angles that were judged in the experiment. The letters correspond to the 19 locations (A–S) in the outdoor scene. The middle letter for each angle (e.g., K in PKR) indicates the central vertex of the angle that was judged.

Figure 4. A photograph of the stimulus angle EGF. The vertex to be judged (G) is indicated by a large orange cone, while the other locations forming the angle (E and F) are marked by small orange cones. This photograph was taken by the first author (J.F.N.) using an Apple iPhone 15 camera.

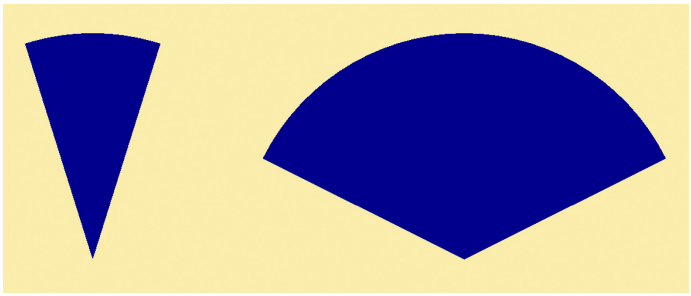

Figure 5. Examples of the adjustable angles used to make the matching judgments in the experiment. On the left, an observer has adjusted the adjustable angle to 35° (e.g., in response to stimulus angle CAE), whereas on the right, an observer has adjusted the adjustable angle to 127° (e.g., in response to stimulus angle KJI).

1° increments/decrements. The observers were given an unlimited amount of time to make their angle matching adjustments. Two sample angle judgments are shown in Figure 5. Our angle matching task resembles that used by Hecht et al. (1999); their observers also adjusted an angle on a handheld device so that it matched that of a three-dimensional stimulus angle on any given trial.

Observers

A total of 30 observers participated in the experiment, 15 younger adults (age range, 18–32 years, mean age, 21.3 years, SD = 3.8) and 15 older adults (age range, 66–80 years, mean 74.3 years, SD = 5.5) from the local community. In our previous experiment (Norman et al., 2015) that found an age-related superiority for visual distance perception, we had a total of 18 observers (9 younger and 9 older). Given that there have been no previous studies related to aging and the visual perception of outdoor angles, the potential effect size of age for the current task is completely unknown. We, therefore, chose a sample size that was considerably larger than in our previous distance perception study (Norman et al., 2015). In the current experiment, we recruited a total of 30 observers, which is 67% more than in our earlier distance study. The observers had excellent visual acuity: the acuity of the younger and older observers (measured with a Precision Vision ETDRS 2195 eyechart) was −0.080 and −0.073 logarithm of the minimum angle of resolution (LogMAR), respectively. Zero LogMAR represents normal visual acuity, and positive and negative values represent worse than and better than normal acuity, respectively. The study was approved by the Institutional Review Board of Western Kentucky University, and each observer signed an informed consent document before testing. Our research was carried out in accordance with the Code of Ethics

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of the World Medical Association (Declaration of Helsinki).

Results

Plots of all individual observers' functions relating actual and perceived angles are shown in Figures 6 and 7 for the younger and older observers, respectively. The results of the best-fitting linear regressions are also indicated. The average (mean) Pearson *r* correlation coefficients were 0.859 and 0.861 (individual *r* values ranged from 0.61 to 0.98) for the younger and older observers, respectively (all correlations are significantly greater than zero, with *p*s < 0.0016, two tailed). These results indicate that fully 73.8% and 74.1% of the variance in the younger and older observers' judged angles, respectively, can be accounted for by variance in the actual stimulus angles within the scene. The analogous overall (i.e., group) results are shown in Figure 8.

The left panel of Figure 9 plots the observers' average signed errors (errors indicating how far each judgement deviated from the actual stimulus angles). If an observer's judgments were accurate (i.e., not biased), then one would expect approximately equal numbers of positive and negative errors (sometimes the judged angle would be higher than the stimulus angle and sometimes the judged angle would be smaller than the stimulus angle)—as a result, the average signed error for such an unbiased observer would be zero. If, however, an observer consistently judged the stimulus angles to be higher than they actually were, then the average signed error would be positive; similarly, if an observer consistently judged the stimulus angles to be smaller than they actually were, then the average signed error would be negative. We conducted a single independent

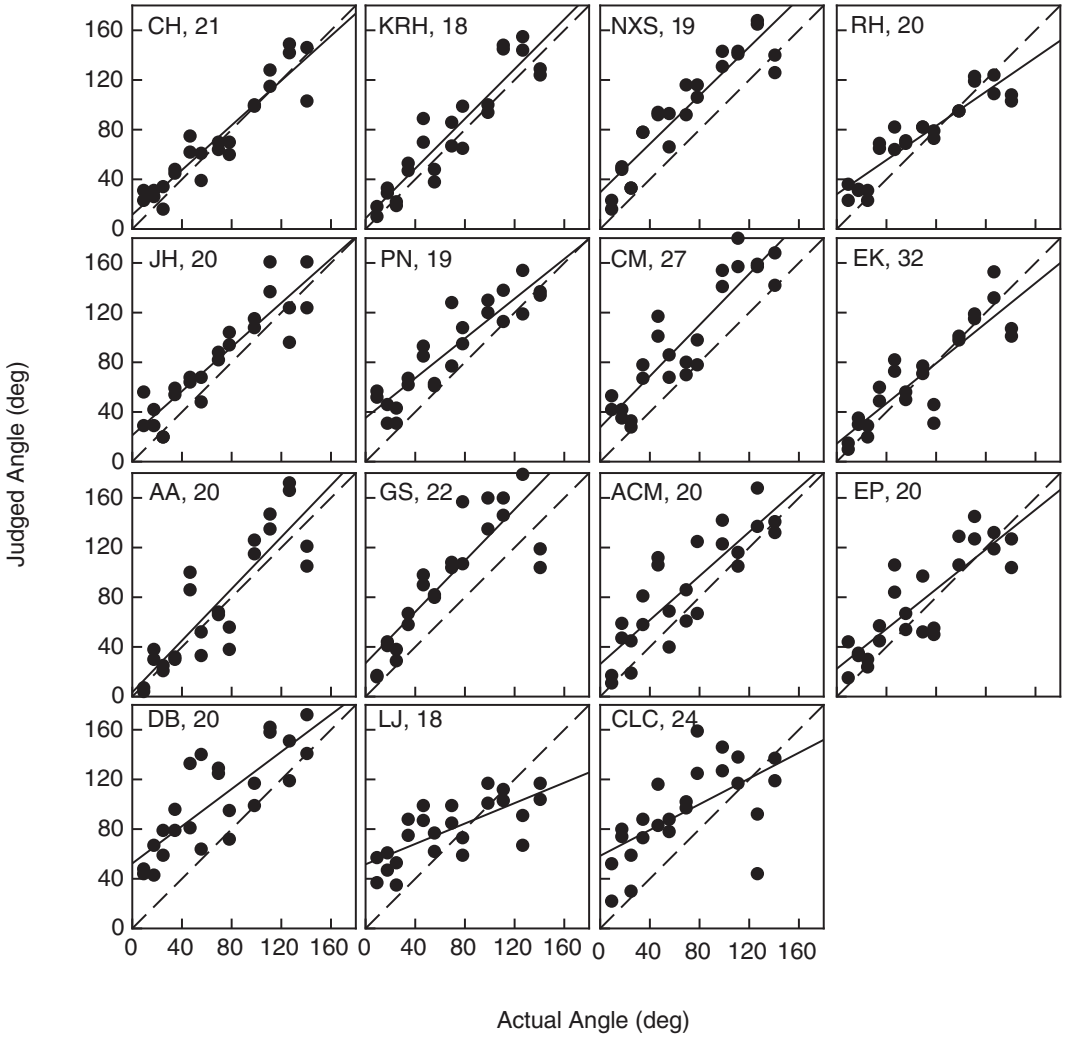

Figure 6. Experimental results for individual younger observers. The 15 younger observers' judged angles are plotted as functions of the actual stimulus angles. The dashed lines indicate perfectly accurate performance, and the solid lines indicate the results of the best-fitting linear regressions. The Pearson r magnitudes decrease from upper left to lower right.

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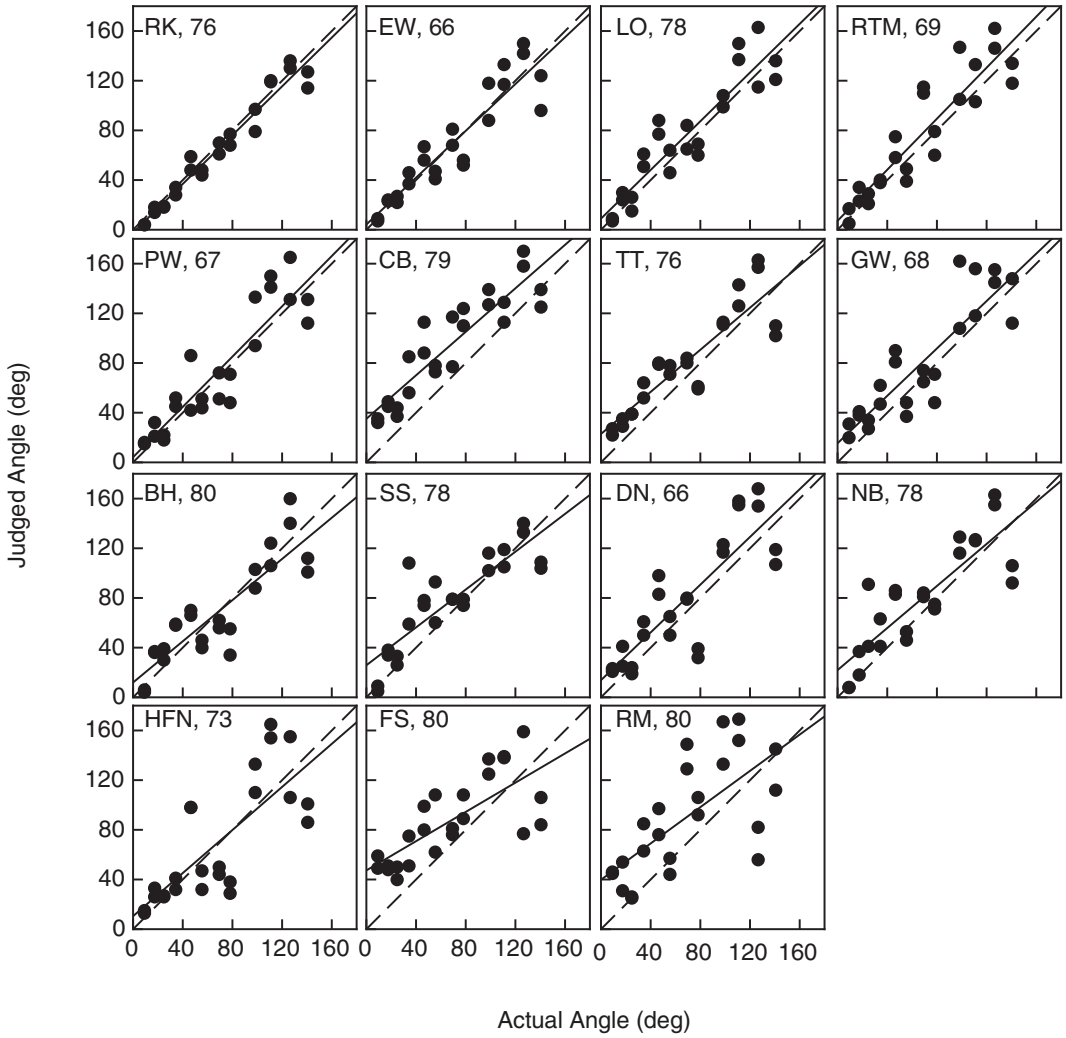

Figure 7. Experimental results for individual older observers. The 15 older observers' judged angles are plotted as functions of the actual stimulus angles. The dashed lines indicate perfectly accurate performance, and the solid lines indicate the results of the best-fitting linear regressions. The Pearson *r* magnitudes decrease from upper left to lower right.

samples *t* test upon the signed errors to determine whether there was any difference in overall accuracy between the younger and older observers. The effect of age was significant, $t(28) = 1.98$, $p = 0.029$, one tailed. Cohen's d was 0.724, indicating that this effect of age upon overall accuracy was moderate to large in size (a Cohen's d of 0.5 indicates a moderate effect, while a d value of 0.8 indicates a large effect; see Cohen, 1988). The average signed errors were 9.68° for the older adults and 16.7° for the younger adults; the younger observers' signed errors were thus 72.5% higher than those of the older observers. It is interesting that only one observer (R.K., aged 76 years) out of the 30 had a negative signed error (for this observer, judged angles were slightly smaller, on average, than the stimulus angles). Four other observers had very small average signed errors, less than 2° (one younger observer, E.K. , and three older observers: H.F.N., B.H., and E.W.). All of the remaining 25 observers exhibited sizeable positive signed errors, indicating that their judged angles were usually larger than the actual stimulus angles.

A straightforward measure of reliability/consistency/precision is to take the difference between the two judgments each observer made for each of the 12 stimulus angles (a perfectly reliable observer will make the same judgment twice for a particular stimulus angle and the difference will therefore be zero; low difference values, therefore, indicate better reliability/consistency). The right panel of Figure 9 plots the reliabilities of all 30 younger and older observers. One can readily see that the average reliabilities are essentially the same for both age groups (14.2 and 13.4° for the younger and older observers, respectively). There was, not surprisingly, no significant difference between the younger and older observers' reliabilities, $t(28) = 0.46$, $p = 0.65$, two tailed.

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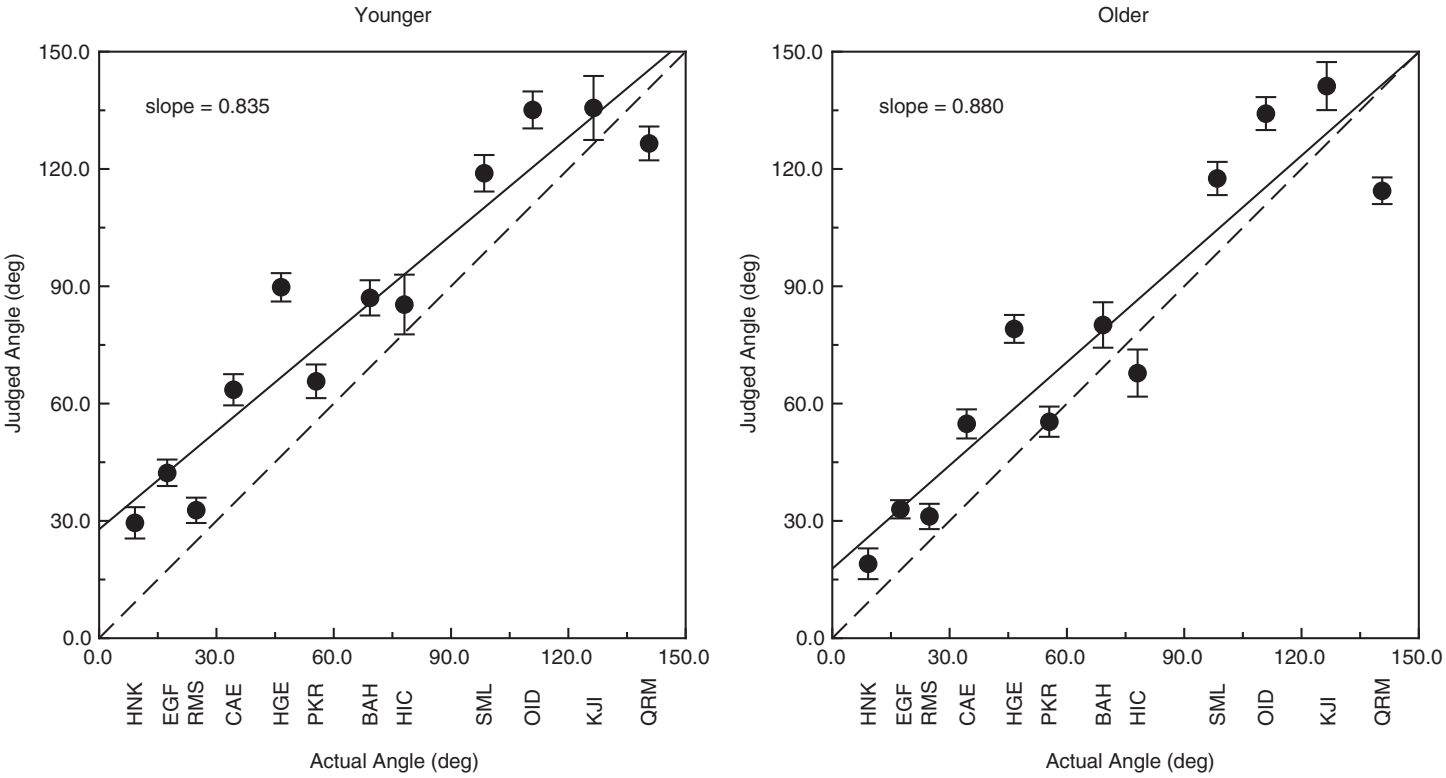

Figure 8. Overall (group) results for the younger (left) and older (right) observers. The observers' judged angles are plotted as a function of the actual stimulus angles. The dashed lines indicate perfectly accurate performance, and the solid lines indicate the results of the best-fitting linear regressions. The error bars indicate ± 1 SE.

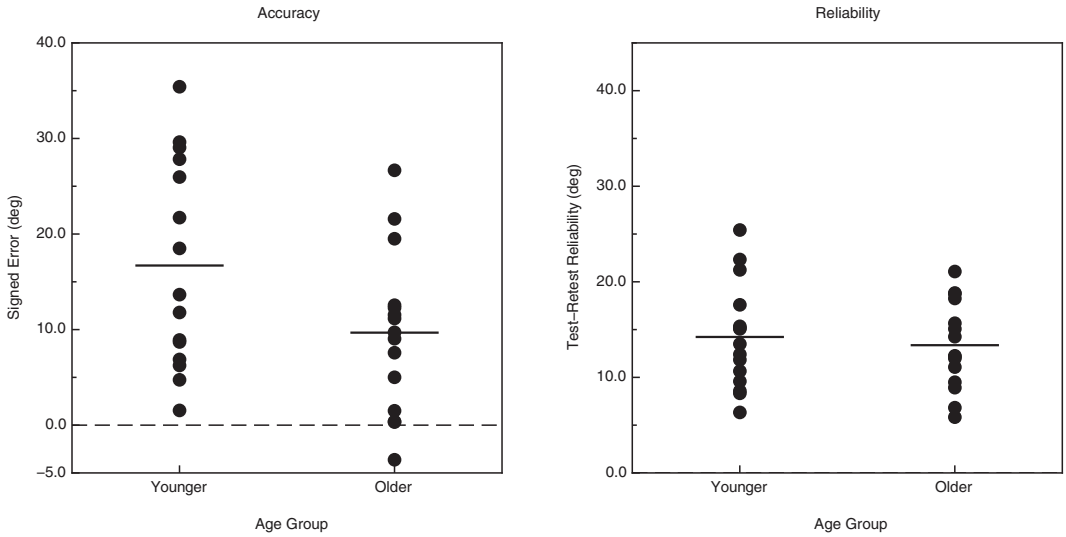

Figure 9. Experimental results for all 30 individual observers (15 younger adults and 15 older adults). Results depicting the observers' overall accuracy (errors between judged angles and the actual stimulus angles) and reliability (average magnitude of the difference between the two judgments made for each of the stimulus angles) are plotted on the left and right, respectively. The horizontal line segments indicate the mean values for each age group for each measure (accuracy and reliability).

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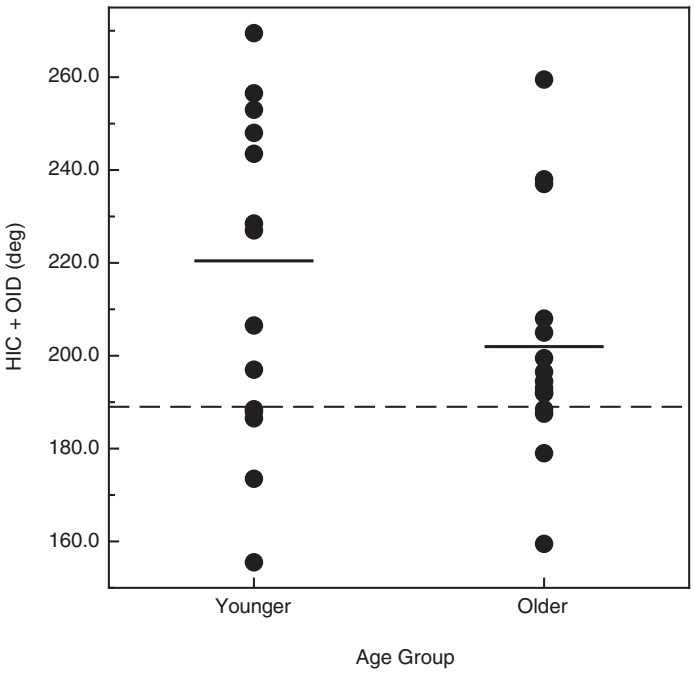

Figure 10. Experimental results for all 30 individual observers (15 younger adults and 15 older adults). Results for each observer depicting the sum of their overall judgments for angles HIC and OID—the sum of the actual stimulus angles for HIC (78.1°) and OID (110.9°) equals 189°. Although the actual sum of these stimulus angles equals 189° (indicated by the dashed line), it is readily apparent that the sum of the judged values of those two stimulus angles frequently deviates (to a large extent) from the physical value. The horizontal line segments indicate the mean judgments of HIC plus OID for each age group.

In the next analysis, we wanted to evaluate to what extent the observers' judgments were consistent with Euclidean geometry. Consider Figure 2, which shows an overhead view (i.e., a map) of the layout of the stimulus objects/locations used in the current experiment. Notice that locations O, I, and H form an almost straight line in depth away from the observer, O being quite close and H being quite far. Also notice that two of the stimulus angles (HIC and OID) are almost complementary angles (complementary angles sum to 180°), and sum to 189°. Stimulus angles HIC and OID are almost complementary and encompass nearly the entire right half of the experimental scene, from very near to quite far. If the observers' judgments are consistent with Euclidean geometry, then each observers' overall judgments for HIC and OID should sum to 189°. Figure 10 plots this sum of judgments (HIC + OID) for all 30 individual younger and older observers. There is a lot of variability between observers, but it is interesting to note that the majority of the observers (17 of 30) have sums that are considerably above the 189° one would expect from Euclidean geometry. Using two one-sample t tests (with Bonferroni-corrected alpha values), we compared each age group's judgments (of HIC and OID) to the expected sum of 189°. As a group, the younger observers' judgments (e.g., median was 227°) were significantly greater than 189°, $t(14) = 3.2$, $p = 0.007$, two tailed, and the effect was large (Cohen's d was 0.82). The older observers, as a group, also had greater values than 189° (e.g., median was 195°), but their deviation from the expected value (189°) was not significant, $t(14) = 1.98$, $p = 0.067$, 2-tailed. This outcome, that the younger observers' judgments of HIC and OID (almost perfectly complementary angles that encompass the entire right half of the experimental scene, from near to far) are significantly greater than 189°, represents a significant departure from Euclidean geometry. This finding is also inconsistent with other geometries, such as elliptic and hyperbolic geometry (Norman, Carmichael, Hagan, Mishchuk, et al., 2025), that have sometimes been found to be consistent with performance for space-related tasks.

As discussed, the overall performance of both groups of observers was good—a full 74% of the variance in the observers' judged angles could be accounted for by the variations in the physical stimulus angles themselves. A visual inspection of the overall results shown in Figure 8 suggests that much of the remaining variance is not due to random error, but is systematic. Notice, for example, that for both age groups, the stimulus angle HGE (physical angle was 46.5°) was substantially overestimated and was, in fact, perceived as being greater than stimulus angle PKR (whose physical magnitude was 55.5°). Thus, HGE and PKR were perceptually "reversed." Similarly, even though stimulus angle QRM had the largest physical angle within the scene (140.6°), it was perceived as being smaller than both KJI and OID (whose physical angles were 126.4° and 110.9°, respectively) by both the younger and older observers. To confirm whether such deviations did, in fact, represent systematic effects and were not simple coincidence (i.e., error variance), we conducted an order analysis like that described by Kendall and Babington Smith (1939). For each individual observer, a rank of 1 was assigned to the stimulus angle that was judged to have the highest value, a rank of 2 was assigned to the next-to-highest judged value, and so on. This process was continued until a rank of 12 had been assigned to the stimulus angle that was perceived to be smallest (it is interesting that the rankings were essentially identical for both age groups; there was no difference between the rankings of younger and older adults, $F(1,28) < 0.001$, $p = 1.0$). A graphical depiction of the results of this order analysis is shown in Figure 11—a quick inspection shows that the perceived order of the stimulus angles was somewhat different than the physical order of stimulus angle magnitudes. For example, even though stimulus angle QRM was physically the largest stimulus angle,

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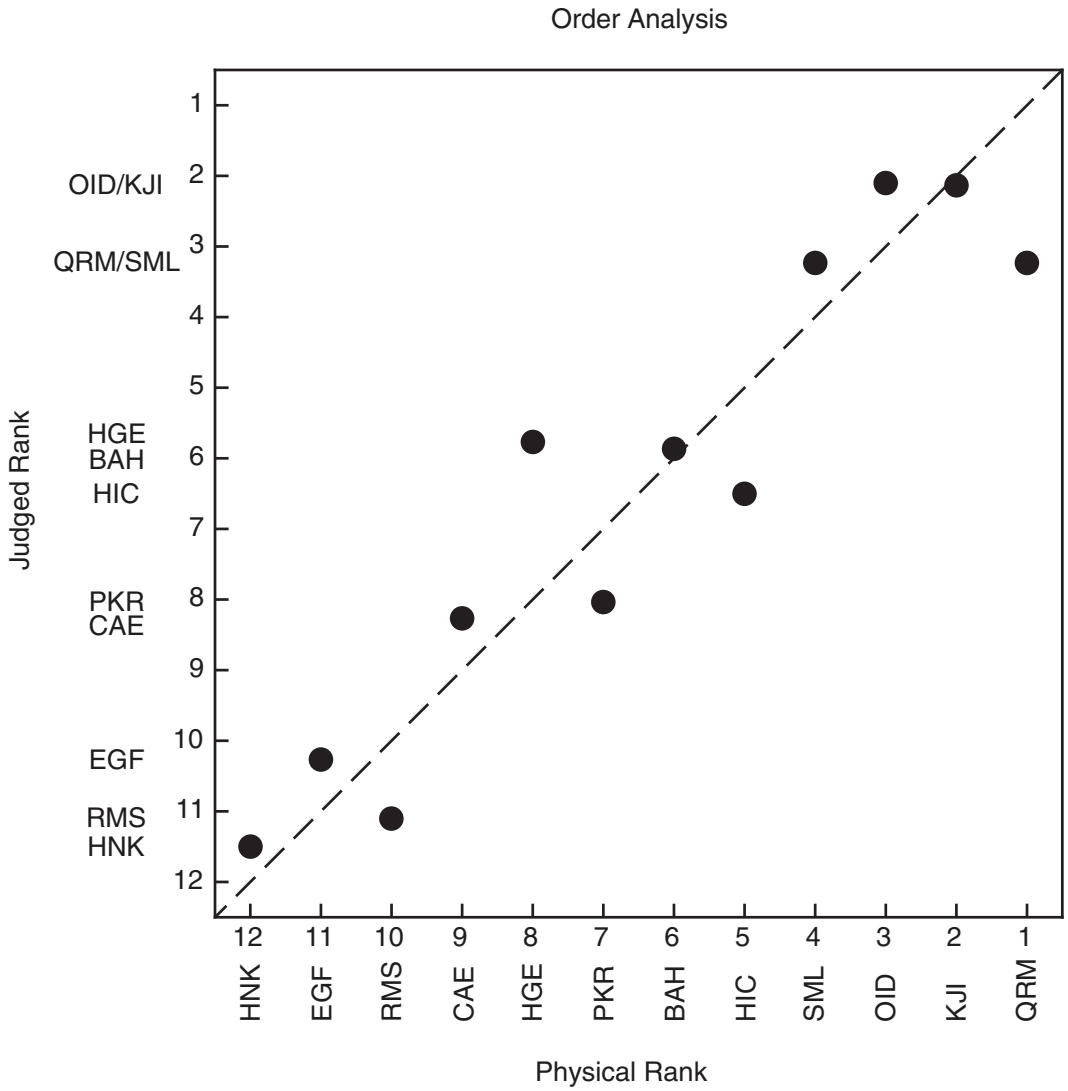

Figure 11. Results of an order analysis of the observers' judgments. For each observer, a rank of 1 was assigned to the stimulus angle that was judged to have the highest value, a rank of 2 was assigned to the next-to-highest judged value, and so on. This process continued until a rank of 12 had been assigned to the stimulus angle that was perceived to be smallest. The dashed line indicates what the results would look like if the perceived order of stimulus angles was the same as that of the physical order of stimulus angles. Note that the results of this analysis demonstrate that the stimulus angles' perceived order is somewhat different from that of the actual physical order.

it was only tied for being perceived as third-highest along with SML, even though the physical angles QRM and SML were quite different (those stimulus angles differed by 42.1°!). Stimulus angle HGE was also perceived as being quite different from what would have been expected. Physically, HGE was the eighth-highest stimulus angle, but its average perceived/judged rank was much higher (average judged rank was much higher, at 5.8). To verify that such effects were systematic across our 30 observers, we then performed a statistical test called the Kendall coefficient of concordance (Siegel, 1956). The test statistic is W, which has possible values that range from 0 (no agreement/concordance across observers) to 1 (complete agreement/concordance across observers with regard to the order of judgments; in our case, the order of perceived stimulus angle magnitudes). The value of W obtained from our order analysis was 0.885, which is close to the maximum possible value. The significance of the Kendall W statistic can be evaluated using the F distribution as shown by both Kendall and Babington Smith (1939) and Marozzi (2014). In our case, the obtained W value (0.885) was significant, $F(10.9, 317.1) = 222.8$, $p < 0.000001$. These results demonstrate that the order of perceived stimulus magnitudes (which was somewhat different from the physical order of stimulus magnitudes) was quite systematic across our 30 observers (i.e., there was a large degree of interobserver

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agreement in the order of perceived stimulus magnitudes).

Discussion

Many studies of environmental distance have found evidence of compression of visual space, such that distances in depth appear substantially shorter than they actually (physically) are (Bian & Andersen, 2013; Da Silva, 1985; Gilinsky, 1951; Hecht et al., 1999; Kuroda, 1971; Loomis et al., 1992; Norman et al., 1996; Norman et al., 2005; Norman et al., 2015; Norman et al., 2020; Norman et al., 2024; Philbeck, 2000; Wagner, 1985)—this perceptual compression can be very large, on the order of 50% or more (such that a 10m distance interval in depth, e.g., appears to be only 5 m in extent). For example results for a typical observer, see Figure 12. This figure illustrates average results (average of three series of judgments) for observer W.V. in an experiment conducted by Norman et al. (2020). In this experiment, an initial marker was placed 6 m away from each observer in depth. The observer then indicated to an experimenter where to place a second marker (along the line of sight) such that the distance between it and the first marker (at 6 m) appeared identical in magnitude to the initial 6 m distance between the observer and the first marker. This process was continued, where the observer placed additional markers (third, fourth, fifth, and sixth) until the observer had created five distance intervals in depth that all were perceived to be identical in magnitude to the initial 6m distance. Notice from Figure 12 that this observer's (W.V.) judgments indicated perceptual compression of in-depth intervals, with the magnitude of the compression becoming larger at farther and farther distances (e.g., the last

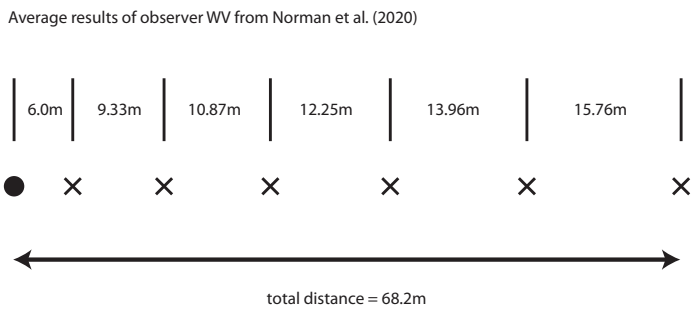

Figure 12. A depiction of the individual results of observer WV from Norman et al. (2020). The observer's vantage point is marked with a filled circle, and the *X*s indicate the final adjusted positions of the orange distance markers. From the observer's point of view, all six of these distance intervals appeared equivalent in magnitude.

distance interval with a physical extent of 15.8 m appeared identical to the 6 m extent nearest the observer, a perceptual compression of 62%). In his investigation, Wagner (1985) found results for an outdoor angle judgment task that were also consistent with compression of visual space along the line of sight (i.e., the depth axis). There is some evidence, therefore, that judgments of both environmental angles and distances reflect perceptual compression in depth.

One of the studies discussed in the Introduction was that of Hecht, van Doorn, and Koenderink (1999); these researchers asked their observers to judge the angles of building corners (vertical dihedral angles where adjacent walls of buildings meet), as well as distances to those corners. Hecht et al. found that their observers' judged angles flattened out with increasing distance, which by itself is consistent with perceptual compression in depth. However, as Hecht et al. correctly point out (p. 1284), "If subjective space is, in some sense, uniformly distorted, errors in perceived distance should fit together with angular distortion." That is, if there is a perceptual compression of visual space itself, it should affect (in a predictable and commensurate way) both perceived distance and perceived angles. This did not happen in the Hecht et al. study. In their experiment 1 (viewing of real-world angles), perceived distances remained approximately consistent with Euclidean geometry, while perceived angles became "flatter," consistent with affine compression of visual space in depth. Accordingly, Hecht et al. concluded (p. 1284) by saying "our results agree better with contentions that visual space cannot be modeled by any standard geometry … than they agree with models of metric distortion."

The results of our current experiment (e.g., see Figure 8) are also inconsistent with a uniform compression of visual space in depth. To see this, consider Figure 13. The left panel shows a view of our actual experimental scene, while the right panel shows the experimental scene following a compression in depth of 45% (in his experiment, Wagner [1985] found perceptual compression in depth of approximately 53% for distance judgments and about 52% for angle judgments). By comparing the left and right panels of Figure 13, one can readily see what our observers' angle judgments should have been if our observers' visual space was uniformly compressed in depth in the manner described by Wagner. Notice, for example, that some of our stimulus angles (e.g., BAH, highlighted in purple) should become "flatter" (or increase in magnitude) with perceptual compression, but that other stimulus angles (e.g., SML, highlighted in light blue) should become smaller in magnitude with perceptual compression. A quick reference to Figure 8 will show that this did not happen. For example, instead of stimulus angle SML being perceived as being smaller in

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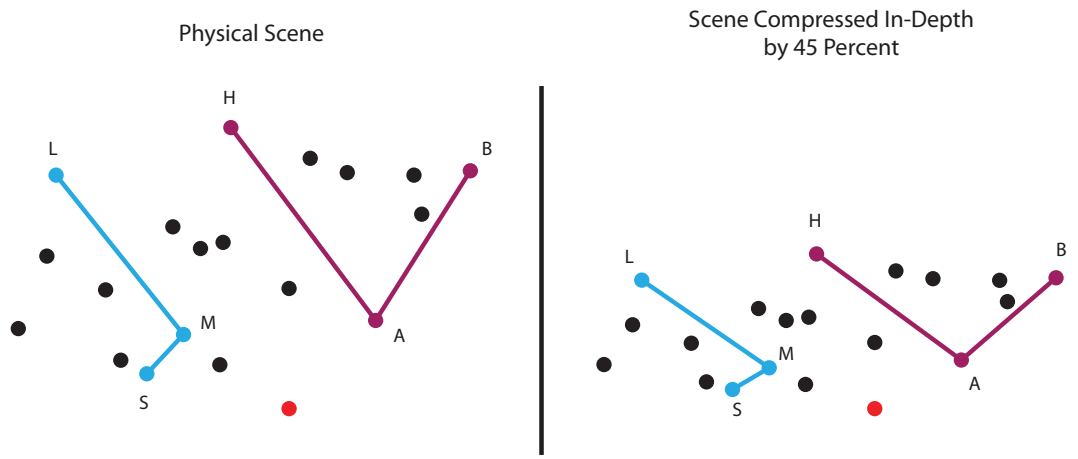

Figure 13. (Left) An overhead view of the actual spatial arrangement of objects in the scene; the letters correspond with those used in Figures 1 and 2 and indicate the locations of trees, signs, light poles, and stone benches. The red circle indicates the viewpoint/location of the observers. (Right) An overhead view where the entire experimental scene has been uniformly compressed in depth by 45% (in the mapping between physical and perceived space, substantial compression in depth is a frequent finding in the literature). Notice that some angles in the experimental scene (e.g., BAH) become larger when space is compressed, whereas other angles (e.g., SML) become smaller when space is compressed. In both panels, the stimulus angle BAH is highlighted in purple, whereas the stimulus angle SML is highlighted in blue.

magnitude than it actually was, our observers perceived angle SML as being larger than it actually was (whereas stimulus angle SML had a physical magnitude of 98.5°, our observers' perceived magnitude was nearly 20.0° larger, at 118.2°). In fact, our observers' judgments (Figure 8) were only consistent with perceptual compression for five out of the 12 stimulus angles (CAE, HGE, BAH, HIC, and KJI)—the best-fitting magnitudes of compression for these stimulus angles ranged from 23% to 64% (BAH = 22.8%, KJI = 26.2%, CAE = 46.9%, HGE = 53.0%, and HIC = 63.6%). The observers' judgments for three other stimulus angles (SML, OID, and QRM) were consistent with the opposite distortion of space (perceptual expansion in depth; see Lappin, Shelton, & Rieser, 2006), with the magnitudes of expansion ranging from 44% to 176% (SML = 44.3%, QRM = 60.3%, and OID = 175.5%). For the remaining stimulus angles (HNK, EGF, RMS, and PKR), no amount of perceptual compression or expansion in depth was consistent with the observers' judgments. Our findings, therefore, were very different from those of Wagner (1985)—our observers' angle judgments outdoors could not be explained by a uniform perceptual compression of visual space in depth. There were some obvious differences between the two studies. In the study by Wagner, observers made judgments of all possible angles between 10 stakes inserted into the ground in a large and open grassy field. In our experiment, observers made judgments of angles between naturally existing objects (trees, signs, light poles, stone benches) within a typical university campus scene (see Figure 1).

An interesting experiment by Gogel (1972) (also see Dukes, Norman, & Shartzer, 2022; Norman et al., 2022; Blessing, Landauer, & Coltheart, 1967) may help to explain the systematic distortions obtained in the current experiment (that some stimulus angles, such as SML, were perceived as being systematically larger than their physical magnitude, whereas others, such as QRM, were perceived as being systematically smaller than their physical magnitude; remember that the order analysis, the obtained Kendall *W* statistic, demonstrated that these distortions were consistent across the entire set of 30 observers; see Figure 11). The experiment of Gogel (1972) clearly demonstrates that monocular information, such as linear perspective, has strong effects and can dominate (i.e., override) binocular disparity in determining perceived spatial relationships. To understand Gogel's experiment and results, consider Figure 14. In Gogel's experiment, the observers viewed two equidistant points of light (i.e., the red circles indicated in the left panel of Figure 14). A trapezoidally shaped flat surface with converging contours and apparent perspective (specifically, an Ames window; see de Heer and Papathomas [2017] and Ames [1951]) was placed in between the two physically equidistant lights. It is critical to note that this trapezoidal Ames window was slanted (at a 45° angle relative to both the fronto-parallel plane and the line of sight) such that the narrow side was physically closer to the observer, and the wide side was physically farther from the observer (as illustrated in the right panel of Figure 14). Because of this, even though binocular disparity was indicating that the narrow side

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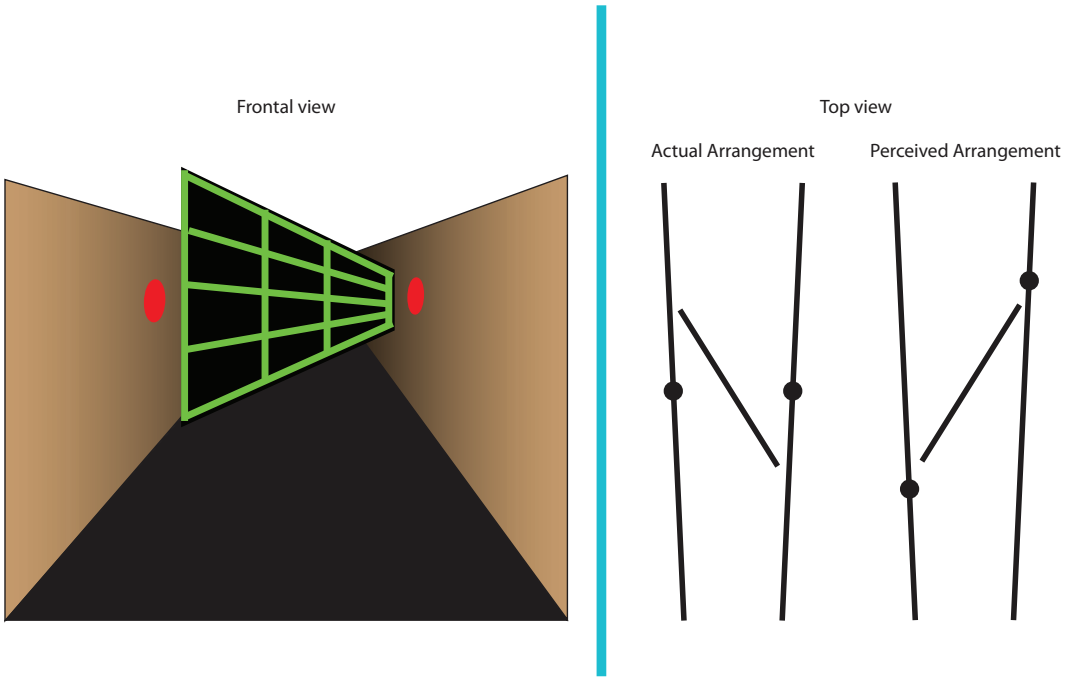

Figure 14. (Left) A frontal view (from the observers' point of view) of the stimulus used by Gogel (1972). The red circles indicate equidistant points of light (equal distances from the observer). A trapezoidal flat surface is actually (physically) slanted in depth as shown on the left in the right panel (the wide side of the trapezoidal surface is actually farther from the observer, and the narrow side is located closer to the observer). Because of the trapezoidal shape of the surface and the apparent perspective provided by the contours on the trapezoid, the surface was perceived as slanted in the opposite direction in depth, as shown on the right in the right panel. The presence of the apparent perspective produced a shift in the perceived positions of the two physically equidistant points of light. Because the wide side of the trapezoidal surface was perceived to be closer in depth, the light directly adjacent to it was pulled forward in depth; similarly, because the narrow side of the trapezoid was perceived to be farther away, the light directly adjacent to it was pulled backward in depth. The presence of perspective altered the perceived spatial arrangement of nearby objects.

of the trapezoidal window was closer to the observer in depth, the apparent linear perspective provided by the contours of the trapezoidal window provided optical information to suggest that the narrow side was located farther in depth. Thus, contradictory information about the slant of the Ames window was being provided by binocular disparity and linear perspective. The interesting result that Gogel (1972) obtained was that the insertion of the trapezoidal window (containing perspective) caused the equidistant points of light to alter their perceived position in depth, such that the left point of light appeared to be located adjacent to the perceived location in depth of the wide side (i.e., appeared closer to the observer in depth), while the right point of light appeared to be located adjacent to the perceived location in depth of the narrow side (i.e., appeared farther from the observer in depth). The presence of the linear perspective caused the two lights to alter their perceived spatial relationship so that their perceived positions in depth were quite different from how they would otherwise have been perceived. The critical finding was that the perspective present within the scene had the power to alter the perceived spatial arrangements of nearby objects. Gogel concluded (p. 180) that "it is clear that … the trapezoidal window was perceived at an illusory orientation that induced an error in the perceived depth between a pair of physically equidistant lights, when these lights were in the depth vicinity of the window."

As just discussed, Gogel (1972) demonstrated that the presence of perspective can alter nearby objects' spatial arrangements and perceived positions in depth. We believe that something similar occurred during the current experiment. Consider Figure 11 and the most obvious perceptual reversals that occurred during our experiment: 1) stimulus angles HGE versus PKR, 2) angles OID and KJI versus QRM, and 3) angles EGF versus RMS. Just as in Gogel's (1972) experiment, there happened to be a prominent sidewalk (see Figure 1) right in the middle of our experimental scene, a sidewalk that produced lots of perspective from the observers' point of view (this was unplanned; in the beginning, we did not anticipate that the presence of the sidewalk could potentially affect/distort our observers' judgments). First consider angles HGE and PKR: HGE was perceived to be much larger than

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PKR, despite the fact that PKR was physically larger. Note that the centroid of HGE is directly adjacent to the sidewalk, whereas the centroid of PKR is located considerably away from the sidewalk to the left—indeed locations P and R are at the very left portion of the experimental scene. Now consider angles OID and KJI versus QRM. The center vertices of OID and KJI are directly adjacent to the sidewalk, whereas QRM is located considerably to the left. Once again, the angles with centers directly adjacent to the sidewalk are perceived as larger (OID and KJI), whereas the distant QRM (to the left, away from the sidewalk) is perceived as being smaller (despite the fact that QRM is much larger physically than OID; QRM was physically 140.6°, whereas OID's physical magnitude was 110.9°). Finally, consider angles EGF and RMS. The center vertex of EGF is directly adjacent to the sidewalk (and was perceived as larger than RMS, despite the fact that RMS is physically larger), whereas RMS is located considerably to the left and away from the sidewalk. Although the presence of the sidewalk was unplanned (and its potential effect was unanticipated) in our experiment, it nevertheless appears that the perspective associated with the sidewalk produced (the perspective is quite obvious and large in the photograph provided in Figure 1) significant local distortions in the specific angles that our observers perceived (angles with their centers adjacent to the sidewalk were generally perceived as being larger, whereas angles with the centers located away from the sidewalk were generally perceived as being smaller). If our conclusion is correct, it would appear that the presence of significant amounts of perspective can alter perceived angles as well as the positions of objects in depth (Gogel, 1972). In our own laboratory's previous research (Dukes et al., 2022; Norman et al., 2022), we have found linear perspective to be important in determining perceived object size and distance.

When considered as a whole, the results of our current experiment are inconsistent with visual space being Euclidean or an affine-compressed version of Euclidean space. This finding is similar to that of several previous studies. For example, Svarverud, Gilson, and Glennerster (2012, p. 1) "found that there was no consistent depth ordering of objects that can explain the distance matches participants made in this environment (e.g. A>B>D yet also A<C<D) and hence no single one-to-one mapping between participants' perceived space and any real 3D environment." Similarly, Foley, Ribeiro-Filho, and Da Silva (2004) concluded that, although "the perception of location and the perception of extent are related, they are not related by Euclidean geometry, nor by any metric geometry." Finally, Koenderink (2012) concluded that visual space is not homogeneous. He said (p. 23), "If vision were veridical, then visual space would be a faithful copy of Euclidean space. In practice this is only approximately the case. Although visual space shares its dimensionality (three, or maybe two plus one) with Euclidean space, it is definitely not a homogeneous space." In another article, Koenderink (2017) concludes (p. 124) that "Evolution optimizes utility … not veridicality." Our current and past results (Norman et al., 1996; Norman et al., 2005; Norman et al., 2015; Norman et al., 2020; Norman et al., 2022; Norman et al., 2024) support this view—although our perceptions of the environment do not enable us to judge environmental distances and angles with completely accurate metric knowledge that is independent of contextual factors (such as the effect of nearby perspective discussed earlier), our perceptual abilities are nevertheless sufficient (Loomis et al., 1992) to enable successful everyday behavior (and perhaps that is all that really matters). Our current findings are in some important ways similar to those of Hecht et al. (1999), who found overall good performance for angle judgments outdoors (e.g., errors generally less than 10°) but nevertheless found effects of context. Hecht et al. (1999) concluded by saying (p. 1269) "The flattening of vertical angles cannot be explained by a linear distortion of the entire visual space. We suggest that, for natural scenes, compression of space is local and dependent on contextual information."

The current experiment (see Figures 9 and 10) and four previous experiments (Bian & Andersen, 2013; Norman et al., 2015) found that aging was accompanied by improvements in accuracy of tasks that involve two fundamental aspects of spatial perception (the ability to judge environmental distances and angles). It is of course true that our perceptual abilities depend on neuronal functioning (i.e., neurophysiology) within the brain; neuronal functioning itself depends on appropriate activation of receptors by neurotransmitters and neuromodulators. In the context of the current experiment and others (Bian & Andersen, 2013; Norman et al., 2015), it is quite interesting that for normal (non-senescent) mammals and primates, decreased activity at gamma-aminobutyric acid (GABA) receptors is associated with improved performance for spatial tasks (Froestl et al., 2004; Helm et al., 2005; Liu et al., 2014; Mondadori, Jaekel, & Preiswerk, 1993; Nishimura, Ortiz, & Conrad, 2017; Stäubli, Scafidi, & Chun, 1999; Sunyer, Shim, An, Hoger, & Lubec, 2009); in other words, when GABA antagonist drugs (e.g., SGS742/ CGP36742, CGP 35348, bicuculline, and 2-OH saclofen) are given to mammals and primates, they block and thus reduce activation of GABA receptors, altering neuronal activity. This is important, because increases in age (i.e., aging) are also accompanied by reductions in GABA activity, even within visual cortex (upon which our perceptual abilities depend). The effect of aging (upon GABA activity), therefore, is similar to the effect of giving a GABA antagonist drug to a non-senescent (not aged) mammal or primate. One consequence of

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age-related reductions in GABA activity is reduced selectivity of V1 neurons to orientation (Leventhal, Wang, Pu, Zhou, & Ma, 2003; Schmolesky, Wang, Pu, & Leventhal, 2000), and reductions in MT neurons' selectivity to speed (Yang et al., 2009) and direction (Liang et al., 2010). This age-related reduction in GABA activity can either reduce visual performance (Norman et al., 2007; Norman et al., 2013; Tadin et al., 2019) or facilitate/improve visual performance, depending on the task. For example improvements, see the experiments by Betts, Taylor, Sekuler, and Bennett (2005) and Hutchinson, Ledgeway, and Allen (2014). Because age-related reductions in GABA activity have already been shown to improve some aspects of visual performance in older adults (Betts et al., 2005; Hutchinson et al., 2014) and it is well-known that GABA antagonist drugs (which mimic some effects of aging in non-senescent mammals and primates) can improve spatial performance (Froestl et al., 2004; Helm et al., 2005; Liu et al., 2014; Mondadori et al., 1993; Nishimura et al., 2017; Stäubli et al., 1999; Sunyer et al., 2009), it is likely (or at least plausible) that our current findings of an age-related improvement in accuracy (Figures 9 and 10) and those of past analogous experiments involving the judgment of environmental distance (Bian & Andersen, 2013; Norman et al., 2015) are associated with the reductions in GABA activity in visual cortex that accompany aging.

Conclusions

In this evaluation of the ability of human observers to judge angles within a natural outdoor scene (Figure 1), we found that overall performance was quite good—about 74% of the variance in the observers' judged angles could be accounted for by variance in the actual physical angles between stimulus objects (trees, signs, light poles, and stone benches). We nevertheless found an age-related superiority (Figure 9) such that our older observers were able to judge environmental angles with better accuracy than younger adult observers (Cohen's d indicated a moderate-to-large effect of age, $d = 0.724$). Although the older adults in our study exhibited better accuracy, their judgments were no more precise than those of younger adults. The current findings (relating to perceived angles) are thus analogous to those of Norman et al. (2015) (who found that older adults' judgments of distance were also more accurate, but not more precise, than the judgments of younger adults). Detailed aspects of our results are inconsistent with the idea that visual space is either Euclidean or an affine-compressed version of Euclidean space. When one considers both the current results and those of our past research (Dukes et al., 2022; Norman et al., 2005; Norman et al., 2015; Norman et al., 2020; Norman et al., 2024; Norman, Carmichael, Hagan, Mishchuk, et al., 2025), it becomes clear that no standard metric geometry can explain the totality of the obtained results.

Keywords: spatial vision, visual space

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